

Estuarine Turbidity, Flushing, Salinity, and Circulation

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One of the stated objectives of this conference is to identify the primary environmental problems of the Chesapeake Bay area. I am aware of and have contributed to three major studies that identify the primary environmental problems of the Chesapeake Bay: The Corps of Engineers' study of the Chesapeake Bay; the State of Maryland's interagency planning study of the Chesapeake Bay; and the free-institution NSF-sponsored study of the Chesapeake Bay. Another, not too recently, was the State of Maryland-sponsored Smithsonian-run study by a committee of experts on problems of the Maryland portion of the Chesapeake Bay. At least these studies encompassed the whole Bay, and included management of research programs in the Chesapeake Bay. So, it seems that we have had adequate studies to identify the primary environmental problems of the Chesapeake Bay.

As a point of departure at this conference, we might have started by taking one of these studies and then asking what sensors might do. When I mentioned this to some of my colleagues they indicated that only half of the audience will have heard me before on these subjects. However, for the benefit of the other half of the audience I will describe the distribution of salinity and the circulation pattern, as well as speak about turbidity and flushing.

First note that the Chesapeake Bay is the largest estuary on the Atlantic coast of the United States. Estuaries may be grouped according to their geomorphological character, and the Chesapeake Bay falls into the group called "coastal plain" or "drowned river-valley" estuaries. According to one subclassification of such estuaries are what are called "partially mixed" estuaries; that is, the vertical structure while showing some variation in density, salinity, temperature, and other properties with depth does not exhibit the sharp interface that occurs at such salt-mud estuaries as the Mississippi where the tidal velocities are very small. In the Chesapeake Bay the tidal velocities are large compared to the velocities that would be induced by the river flow alone. Consequently, the Chesapeake Bay has partial vertical mixing.

SALINITY

The Chesapeake Bay roughly is 180 miles in length and 40 miles at its widest point. The main river is the Susquehanna, supplying 50 percent of the total fresh water that enters the Bay. More important, it brings in between 85 and 90 percent of the fresh water that enters above the mouth of the Potomac. The Potomac, the second major tributary, brings in about 11 percent of the water that enters the Bay. The James is next, bringing in about 5 percent. The York and the Rappahannock together provide about 5 percent, and then all of the rest of the tributaries add their little bit.

The salinity varies regularly up the length of the Bay and up each of the tributary estuaries. The winter average surface value varies from over 23 parts per thousand at the mouth of the Bay on up to less than two parts per thousand near the head of the estuary at the Susquehanna flats. A similar decrease occurs as we move up the Potomac, up the Rappahannock, up the York, and up the James. In general the salinity not only decreases coming up from seaward but also shows a gradient across the Bay. The gradient, with fresher water on the western shore and eastern shore, in part results from more fresh water input on the western side of the Bay. It would occur even if there was only one source of fresh water because of the effects of the Earth's rotation. If we look in detail, say, in the James River where there is one primary source of fresh water, one finds that there is a lower salinity on the

right side looking seaward than on the left side because of the effects of the Earth's rotation. This is a winter condition which is also an average condition for all seasons.

In spring, the salinity decreases at Poole's Island. Where there were about six parts per thousand in winter, there is now about one part per thousand; salinity generally decreases throughout the Bay and throughout all of the tributaries in spring.

In summer, salinity distribution is not too different at the surface than in winter.

Autumn is the time of highest salinity; we find about seven parts per thousand at Poole's Island, increasing to something like 29 at the mouth. This, again, is surface distribution.

Looking at depth distribution for the summer—40-foot distribution of salinity—we also see something about the distribution of depth; actually at 40 feet there are connections made by dredged channels on up the Bay. But, there is a central deeper portion of the Bay nearer the eastern shore over much of the Bay, and the salinities are greater there.

The salinity distribution at 60 feet, again, shows the shape of the Bay: The very narrow channel greater than 60 feet in depth runs along the spine of the Bay as it also does in Pocomoke Sound and some other places. If we ever deepen the channel to 50 feet or more all the way to the sea, some considerable work would be involved. Probably some significant changes in the dynamic structure of the salinity regime would occur if the isolated pockets were connected.

Looking at the salinity distribution along the length of the Bay and along the maximum depth, we see, by vertical exaggeration (compared to horizontal), that the bottom looks rough but it is not that bad. There is a basin in the center with somewhat shallower depth near the mouth than in the central regions if we follow just the deepest portions. The other point that is noticeable is that the water is fresher on the surface than it is at depth. There is a downward pushing of the isolines in the surface layer and upward pushing of the isolines of salinity in the deeper water. This is exactly what happens; that is, typically, the pattern with salinity near the 15-parts-per-thousand line is located at the surface at a point about $37^{\circ} 50'$ north and it intercepts the bottom at $39^{\circ} 5'$ north—a distance of about 70 miles. Hence, there is at any point a vertical gradient in salinity but not a sharp gradient. The surface region has approximately uniform salinity with depth for a ways, then a region of transition, and then in the deeper water, more uniform distribution with depth. This is the appearance of the summer depth distribution.

The spring average shows the salinity distribution moving down with greater vertical stratification.

With respect to salinity surface and bottom salinities vary seasonally; the vertical gradient varies seasonally with the average difference between salinity at the surface and at 40 feet being greatest in the spring and least in autumn; surface salinities are greatest in autumn and least in spring.

CIRCULATION AND FLUSHING

The most obvious water motion in the Bay is motion of the tide. It moves back and forth at speeds varying from one-half a knot to 2 knots, depending on the location. There is a generally increasing tidal current moving up the bay from the mouth, decreasing in the middle reach, and then increasing again in the upper Bay with area constriction such as Sandy Point giving local regions a higher velocity. This oscillatory motion of the tide is superimposed upon a non-tidal circulation pattern, distorting the vertical pattern of the tidal motion.

Current velocities vary from the surface to the bottom during the flood period and during the ebb period. (Of course the flood direction is opposite the ebb direction. The ebb velocity is the velocity during the part of the tide when the water is flowing seaward.) The ebb velocity is stronger at the surface and decreases with depth. The flood velocity is weakest at the surface and increases with depth down to a level near the bottom. So there is a region in which the ebb current exceeds the flood current in the upper layers and a region in which the flood current exceeds the ebb current in the lower regions. If a proper average is taken over the tidal cycle, the velocity varies from the surface—the positive mean velocity toward the sea. The tidal mean velocity goes from some value, in this case about 1500 millimeters (0.5 feet) per second which is about 20 percent of the amplitude of the tidal oscillation, down to zero at 3 meters, and then it increases up the estuary in the lower layers.

This general circulation pattern can be modified. In general we find that the boundary between the seaward-flowing upper layer is thicker on the right-hand side of the estuary looking seaward than on the left. The landward, up-estuary flowing, layer is thicker on the left-hand side of the estuary looking seaward than on the right. This boundary sometimes gets tilted until it intercepts the surface so that we have essentially seaward flowing water in the right side of the estuary looking seaward, and up-estuary flowing water on the left, superimposed on the tide. This does occur in some cases, particularly in the James—the estuary which has been studied so much by VIMS.

Water comes in along the bottom from the ocean into the estuary. It has to flow back out again; it cannot just pile up. The river comes in providing an upper layer flowing seaward, and a layer flows up the estuary from the ocean in the deeper water that must go seaward again. There is some vertical flow from the lower layer to the upper layer all along the estuary, and this augments the flow on the upper layer as it flows out. So there is a very small amount of vertical motion, something like 10^{-5} meter per second. When distributed over the whole horizontal plane at mid-depth, it involves a large volume of water. It can, however, be measured either directly or indirectly. These measurements show that the vertical motion is peak at mid-depth.

A schematic diagram of the way the estuaries behave shows river flow in, and there is an increasing volume rate-of-flow seaward. In the upper layer, there is a flow inward from the ocean and a decreasing landward flow or up-estuary flow in the lower layer. This decreasing flow augments the upper layer and its seaward flow by vertical motion. If in a given river flow, coming well downstream, large volumes of flow accrue in the estuaries. Ten times the river volume flows out and nine times the volume comes in, the difference between the outflow and inflow must always be just equal to the fresh water volume added. This is representative of a very simple estuary.

The Chesapeake Bay is much more complicated because it is an estuarine system involving a number of tributary estuaries. In simple estuary systems, for instance, we would expect that the seasonal variation in salinity would be most pronounced at the upper parts of the estuary and decrease as we move down the estuary and that, in fact, the minimum salinity would occur at the upper estuary first and may be delayed until much later in the season further down the estuary. This is not true in the Chesapeake Bay. Essentially, the minimum salinities occur at almost the same time throughout the Bay within a few weeks—not several months as in some estuaries. Further, it is an interesting thing that the annual range in salinity is constant over about 85 percent of the length of the Bay.

From Poole's Island down to somewhere between the Rappahannock and the York River, the annual range in the salinity is about seven parts per thousand, average. It drops off slightly in the lower 15 percent of the Bay to about five parts per thousand. This is unusual in an estuary that has a single fresh water source. With multiple sources of fresh water coming in the estuaries we have the salinity condition stated above. These are typical salinity variations, with depth: 15 parts per thousand in the upper layer; 18 parts per thousand in the lower layer. We also see that though the vertical motion involves a very weak motion, it involves a large volume of water because the vertical flow is taken over a large area. Note that between two sections where the salinity is 21 and the salinity is 27, twice the river flow is vertical from the lower layer to the upper layer.

Not all estuaries behave in a typical two-layered pattern. The major tributaries such as the Potomac, the James, possibly the York and the Rappahannock do, though not always. The Patuxent estuary behaves over much of its length, say, 2/3 of the time like a two-layered estuary, a typical characteristic estuary. Some of these tributary estuaries do not behave as a two-layered estuary, in particular those with small fresh water inflows. The Patapsco estuary in which the Baltimore harbor is located is an example of this kind of a tributary system to the Chesapeake Bay. The Patapsco is controlled primarily by the fact that in the Bay off the mouth of the harbor there are two processes that control the vertical salinity gradient: The counter motion, which tends to bring fresher water down at the surface and saltier water up at the bottom, trying to make the salinity difference between the surface and the bottom very high, is countered against a vertical mixing which tends to destroy the vertical gradient. The resulting vertical gradient is the result of the balance between these two processes, of counterflow on the surface in the deep waters and the vertical mixings.

Baltimore harbor is on a tributary that does have its own river inflow; the harbor is a drowned river valley, but the fresh water inflow is very small. In fact, it would take 350 days or about a year for the local fresh water inflow to fill the volume of Baltimore harbor. Baltimore harbor and most of the similar small tributaries are essentially filled with Bay water. But as we move into Baltimore harbor, we find that, though the mean salinity top-to-bottom does not change, the distribution changes. In the Bay off the mouth of the harbor we see five parts per thousand at

the surface and 15 parts per thousand at depth, a very strong vertical gradient. At the head of the harbor we see a little over eight parts per thousand at the surface, higher than out in Bay, but at the bottom a little over 10 parts per thousand, lower than out in the Bay.

In other ways, there is less vertical gradient, the point being that there is not the mechanism to maintain the vertical gradient but there is a mechanism of mixing to destroy it. A density situation is now created in which Baltimore harbor looks like the ocean to the surface waters of the Bay; that is, they are fresher, less dense, and so they flow over the top and flow into the harbor. The deeper bottom waters in the Bay are denser than the waters in the harbor so they also flow into the harbor. There are now two inflows, one at the surface and one at the bottom. For continuity an outflow has to take place at mid-depth. So this is a three-layer system and was first discovered for Baltimore harbor.

There are some other tributaries which are not as deep as Baltimore harbor. Baltimore harbor is a unique tributary estuary in that it has a depth essentially equal to the depth of the open Bay. A number of tributaries such as the Severn, South, Back, Bush, and Gunpowder Rivers have depths that interconnect only with the surface layers of the Bay. In these tributary estuaries the flushing and circulation patterns are driven primarily by the density difference between the waters of the Bay adjacent to the mouth of the tributary estuary and the waters in the tributary estuary. Again these are tributaries with relatively low fresh water inflow, and they are essentially filled with water from the Bay. The salinities in these systems lag behind the salinities in the Bay. The salinities are minimum in the spring and maximum in autumn.

The salinities in the Bay are always going through some time variation. During the time from early winter to early summer when the salinities are falling in the Bay, the Bay waters are less saline than the tributaries so the Bay waters flow into the tributary on the surface, and the tributary waters flow out at the bottom. On the other hand, during the time that the salinities in the Bay are increasing, from early summer through late fall, the waters of the Bay are higher in salinity than the waters of the tributary, so the reverse process occurs with inflow of Bay waters along the bottom and outflow along the top. This means that twice a year there is a period of minimum flushing of these tributaries. It would be a problem except that the salinity regime as a simple sinusoidal curve does not work that way. There are short-term ups and downs. These short term ups and downs in the inflow and in the salinity also result in some renewal of water in the tributaries.

The tributaries are essentially pumped by this fluctuation in the salinity regime of the Bay. In Baltimore harbor this kind of flow pattern represents a flow of 17 000 cubic feet per second or about one third the flow of the Susquehanna River. It really initiates because the Susquehanna River contributes heavily to the fresh water supply, creating the density gradient that allows this to go on. The local tidal portions could never do this. Thus, the harbor flushing time or mean-residence time, is about 10 days.

SEDIMENTATION AND TURBIDITY

I was also asked to talk a little about sedimentation and turbidity. I understand turbidity to mean some effect on the optics of the system from suspended material. Most of the suspended material affecting the optics is inorganic suspended sediment. I am going to talk about the clastic sediment in the upper Bay; that is, the fine sediment that essentially exists in suspension in the upper Bay. There are two primary sources of the clastic sediment—the marginal shore erosion sources and the river discharge.

First let us consider the marginal sources. If we look at the system from near Baltimore, across the mouth of the Susquehanna, and on around to Tolchester, we can note either the deposition or erosion in volume, the average volume lot per mile of coastline. We would see that there is very little deposition but that there is highly variable erosion from one coastal segment to the next. Two adjacent segments can show quite large differences in the amount of erosion because of the exposure and the type of soil.

The major input for the upper Bay is the Susquehanna River. The sediment and sediment concentration increase when the river flow increases. That means that in terms of total flux, we are squaring the effects of the river; that is, we not only have a larger volume rate of flow but also high concentration.

Note the periods of time when the sediment supply occurs. During the springtimes of 1966 and 1967, for example, there was a major supply of sediment during each spring. Probably 70 percent of the sediment coming

into the upper Bay occurs within a relatively short time, perhaps as small as two weeks and certainly as small as two months. When the sediment comes in, it is distributed into the upper Bay. For a short period of time there are actually higher sediment concentrations in the Susquehanna and the upper portions of the Bay. The concentration—there is a peak of 60 parts per million—decreases going downstream. This occurs only during the period of a high flow. During the rest of the year, the distribution of suspended sediment, in parts per million, actually is lower in the input source—the river—than it is down in the Bay. We have what we call a classical turbidity maximum. Down in the Bay we notice that the maximum is higher toward the bottom than toward the surface; the turbidity is higher within the Bay than it is in the major source, the Susquehanna River.

Let us examine the reason. Consider the tidal current oscillating about zero, going from maximum ebb to maximum flood. Lines of concentration of sediment at 2 and 4 meters from the surface show that the concentration of sediment was quite steady, being relatively unrelated to the tide. This ranged between 10 and 20 parts per million. Now if we go to the 4- to 6-meter interval, we see at 4 meters not much variation in sediment concentration with time except when the tidal current got quite large; but beginning at 6 meters we see near the times of maximum ebb and maximum flood the concentrations increase, in this case, from about 15 parts per million to over 35 parts per million. Near the bottom (9½ meters), say, at 8 meter depth, the large fluctuation in sediment represents what happens at 9 meters. We notice that at 9 meters, ½ meter off the bottom, the concentration varies from about 20 parts per million at slack water to as high as 280 parts per million at the peak of the ebb or flood tide so that this maximum turbidity is caused by the resuspension of sediment during flood and ebb of the tide. It is probable that the sediments go through this cycle over and over again. This is why if one digs a trench or channel from Poole's Island on up to the C & D Canal and puts the sediments where they can be stirred not only by the tide but by the wind, they are going to be recycled repeatedly until they finally get in the channel again.

During the period of high river flow the fresh water extends from the mouth of the Susquehanna down almost to Poole's Island. If at that time we look near the front where the effects of salinity just begin with depth, a sharp increase in density occurs. During that time there is a high inflow of sediment, and some peak sediments appear, riding on the density layer. This is the only time, however. Mostly, the concentration of sediment is largest at the bottom. But for a short time of year near the front where there is high river flow and there is a fairly sharp front between salt and fresh water, we do see this maximum suspended sediment riding on the turbidity layer.

REMOTE SENSING

One of the things I have been trying to emphasize throughout this paper is the behavior of the circulation of the Bay. It is a pertinent feature in considering, for example, distribution of pollutants, processes that bring juvenile croaker from their spawning grounds into the Bay, or maintaining certain new plankton which migrate vertically with a diurnal cycle and spend practically the same amount of time in the seaward flowing layers as they do in the landward flowing layers. (They are kept from being swept out of the estuary because of this two-layer circulation pattern.) These are things that involve depth in a three dimensional system.

I have not discussed lateral distribution though it has some interesting implications. I have discussed longitudinal and vertical distribution, but if we are going to sense anything about the physical circulation pattern, we have to do it three dimensionally; we have to look vertically. I just mention that because I do not think any remote sensors have this capability.

If we had looked at charts of temperature, we would see generally that temperatures follow the seasonal pattern of air temperature with some modification by the influence of the ocean. That is, the Bay is warmer in the upper end than in the lower end in summer and colder in the upper end than in the lower end in winter. Temperature does exhibit some very large year-to-year and short-term fluctuations at any given point. A sweep through the Bay shows some very large fluctuation with space. It may only appear so since we do not have very many points in which we have long-time climatic information on the distribution of temperature. Particularly, we do not have synoptic data on temperature in which we can say this is the way the temperature pattern looks at a given instant of time to the bioata and hence relate this possible gradient and anomalies in the natural field to what might occur, say, from a heated discharge; one might learn something about this phenomenon from remote sensors.

At a few places we have some daily temperature measurements which can be averaged over monthly and yearly periods. Note that the Bay is very noisy, temperature-wise. A plot of the departure of temperature from the 50-year mean at one location shows that the range in the annual average, plotted for August or February temperatures, gives very similar results. The total range in variation is over 6° F and the year-to-year variation can have averages over as much as a 14-year period almost $1\frac{1}{2}^{\circ}$ F above or below the long-time average. I think that more information on this noisy temperature spectrum would be worthwhile.